

Strategies for increasing yield potential

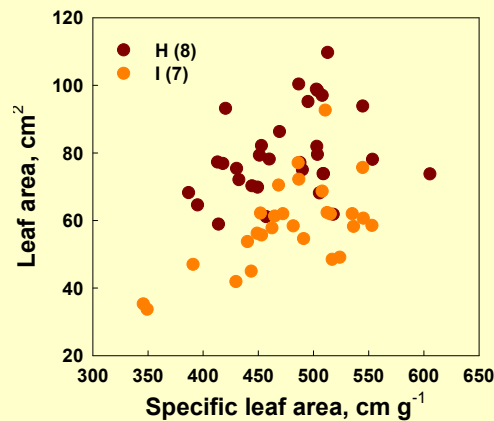
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***2009 IRRI Annual Program Review
13 April 2009, Rooms ABC, DL Umali Hall***

Actual activities to meet the challenges of continuously supply new varieties expressing improved traits for yield potential (in addition to grain quality and resistance to stresses)

- Integrated breeding for grain yield with high-yielding parents from the large populations grown in different breeding nurseries
- Ideotype breeding for the establishment of a desired combination of favorable plant characteristics in a single plant
- Phenotype variability of traits of interest (plant architecture...) and correlation between yield or yield-related traits and traits of interest
- Comparison of the best hybrids and inbreds for trait discovery
 - Yield components
 - Crop architecture at maturity
 - Biomass accumulation
 - Sink regulation
- Multi-locational evaluation and G x E interaction

Thin organs at early stage to favor quicker tillering and leaf area production and higher seedling vigor



Hybrids and inbreds:

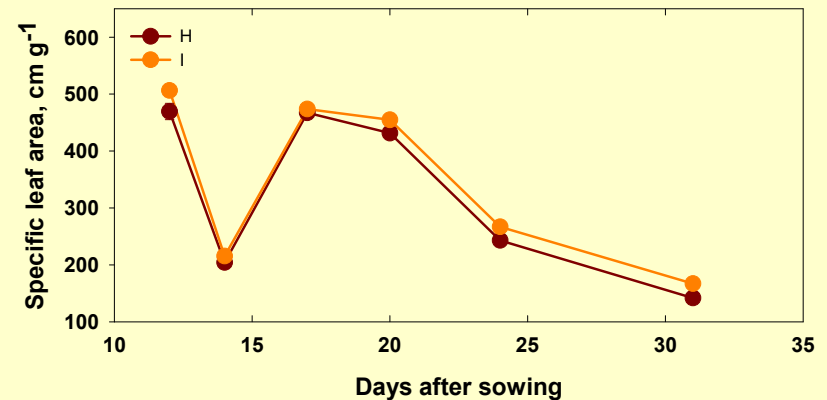
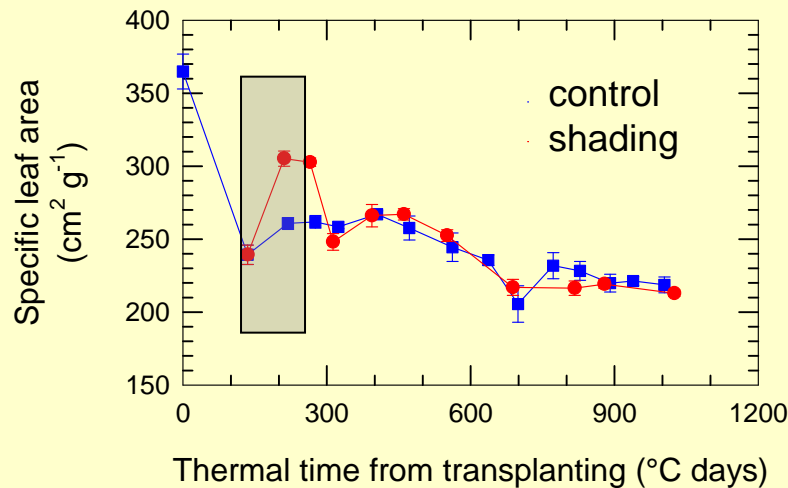
- same range of variation in SLA at transplanting
- positive correlation between leaf area and SLA

Hybrids:

- Higher leaf area of seedlings with respect to SLA

The range of variation in SLA is not the cause of early hybrid vigor but higher SLA can trigger higher leaf area and seedling vigor.

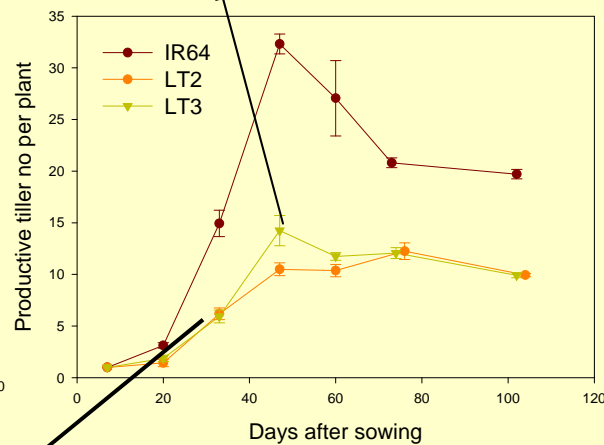
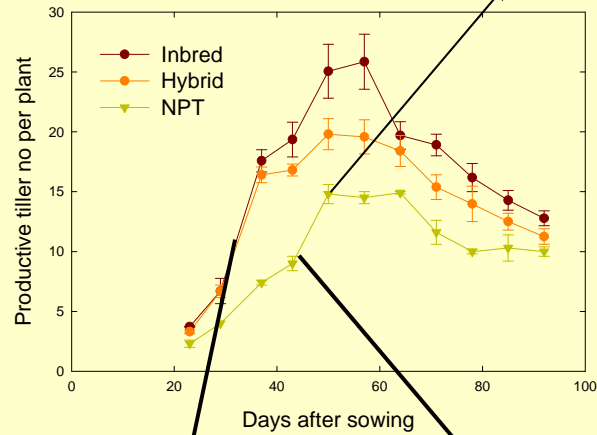
Can plants grow with even higher SLA at early stage?



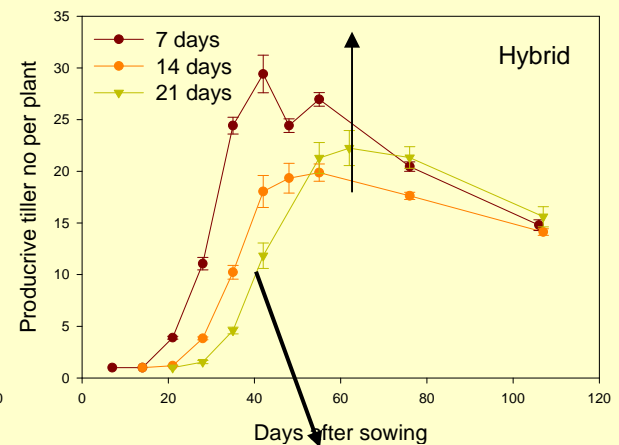
There is room to grow seedlings with increased SLA at early stage (better weed competitiveness)

Higher leaf area at early stage: early and rapid tiller production to rapidly close the canopy and accumulate biomass

Similar maximum tillering time



Later maximum tillering



Lower tiller emergence rate

Similar tiller emergence rate

Early and rapid tillering is essential for high yield, and is already a characteristic of hybrids and inbreds

	GY (t/ha)	TillE
IR64	8.71	0.59
LT2	6.30	0.82
LT3	7.27	0.70

	GY (t/ha)	TillE
7days	7.75	0.50
14 days	6.98	0.68
21days	6.97	0.61

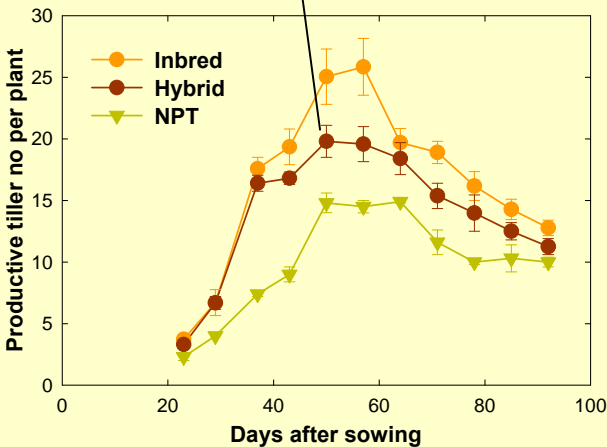
- NPT and LTG: low biomass accumulation because of reduced tillering capacity and more vigorous organs at early stage**

Early cessation of tillering and quick allocation to internodes to increase reserves storage and reduce the vegetative phase

How is tiller cessation regulated when high seedling number per hill?

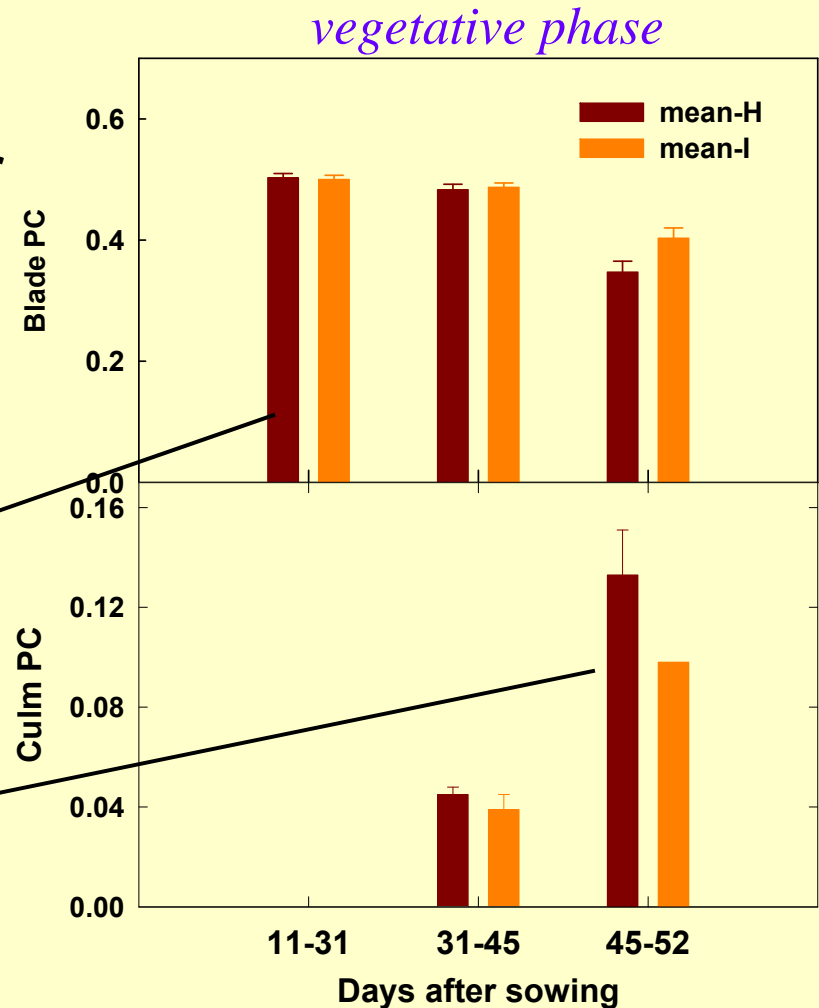
High correlation between stem vigor and reserves accumulation

Earlier cessation in tiller emergence of hybrid is observed at the time of change in sink regulation in favor to culm



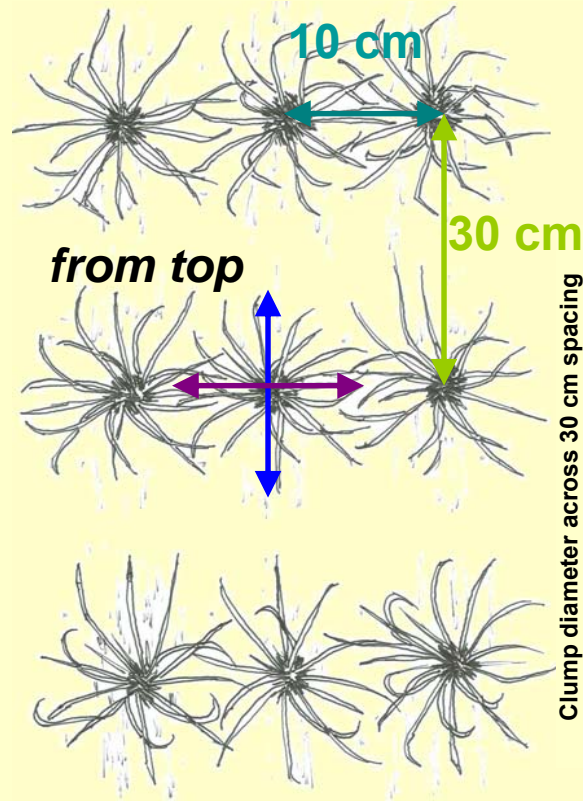
Similar sink regulation until PI

Hybrid:
- quicker increase in allocation to the culm around PI

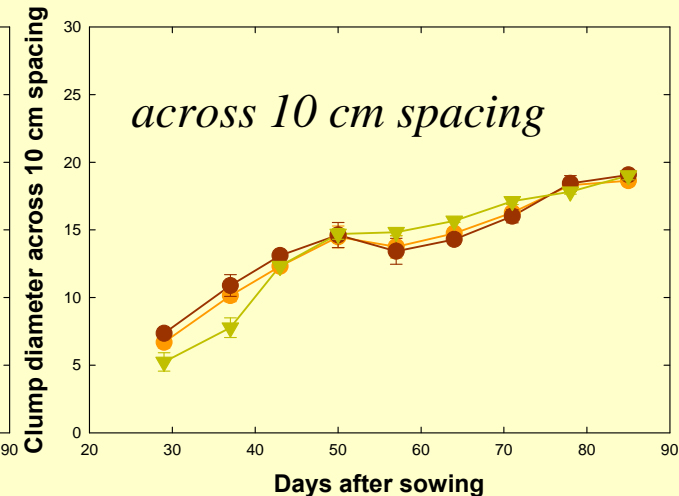
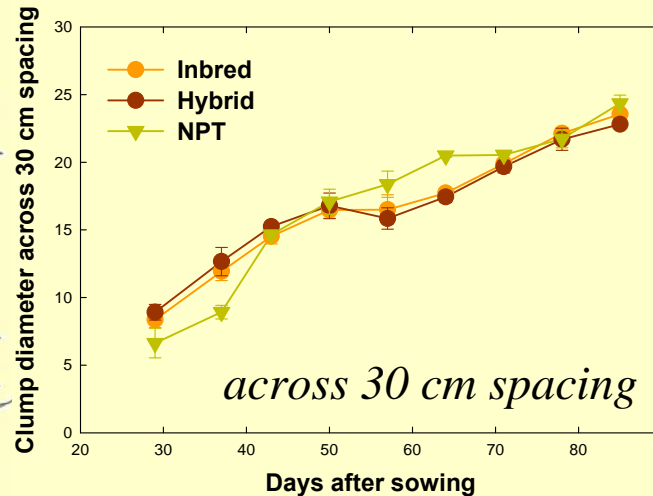


Earlier cessation in tiller emergence could generate an increase in reserves in the culm and an extended grain filling duration (earlier start in grain filling)

More efficient crop architecture at early stage: improving leaf area arrangement under direct-seeding (to reduce open spaces)



Is the plant able to adapt its leaf and tiller orientation according to access for light?



- Same and weak sensitivity of hybrids and inbreds to intra-plant competition:
- No adaptation of IRRI hybrids/inbreds to direct-seeding
 - All the genotypes evaluated here were bred under transplanted conditions and were not supposed to be adapted to direct-seeding
 - The best genotypes selected under transplanting conditions were also the best under direct-seeding conditions

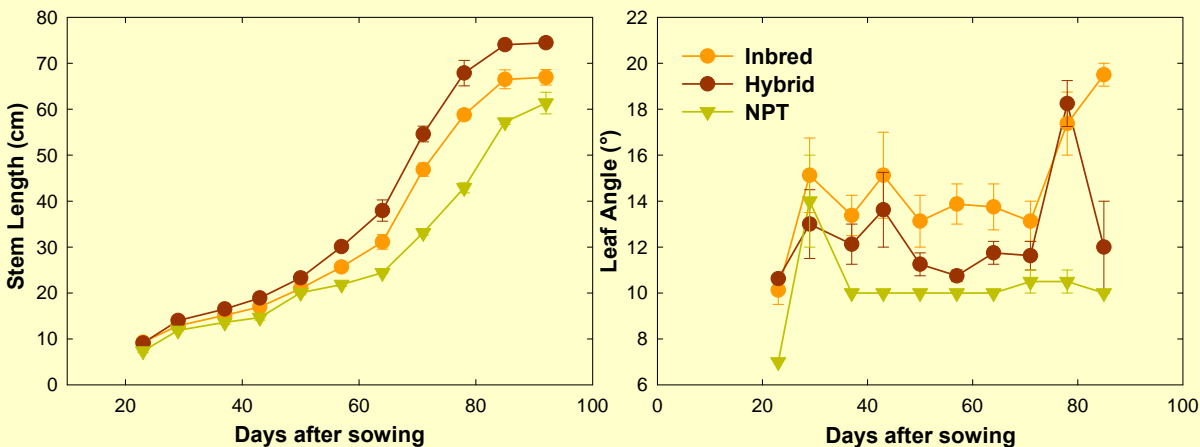
More efficient crop architecture at late stage: improving leaf area arrangement during grain filling (to increase light penetration)

Desire morphological traits near maturity:
(with reference to China's super rice)

- 3-4 leaf tips above the panicle
- low position of the panicle
 - erect tillers and leaves
 - delayed leaf senescence
 - moderate plant height



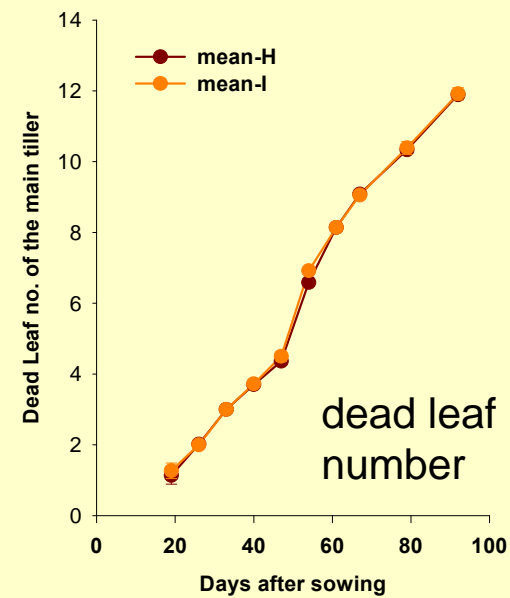
Some differences in plant architecture can already be noticed between IRRI hybrids and inbreds



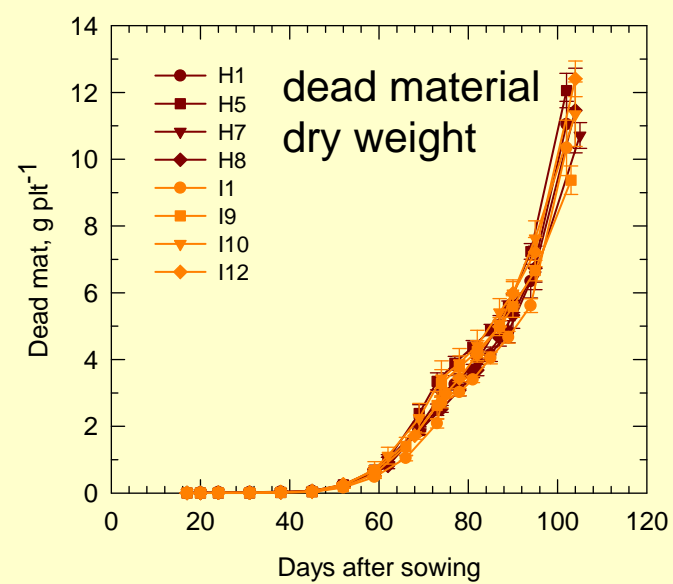
IRRI hybrids are taller and more erect than inbreds

IRRI NPTs appear to have a very rigid structure

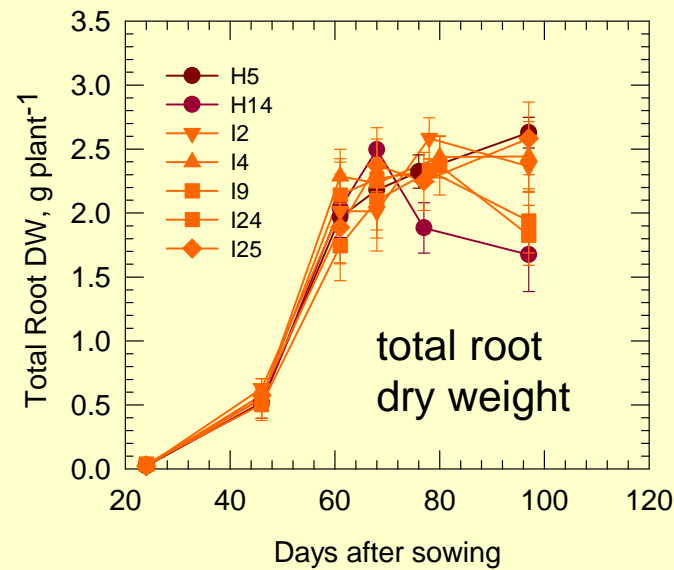
Extended leaf greenness during grain filling to increase light capture and delayed root senescence to sustain N uptake



Same dynamics of leaf senescence in terms of leaf number and leaf dry matter between hybrids and inbreds



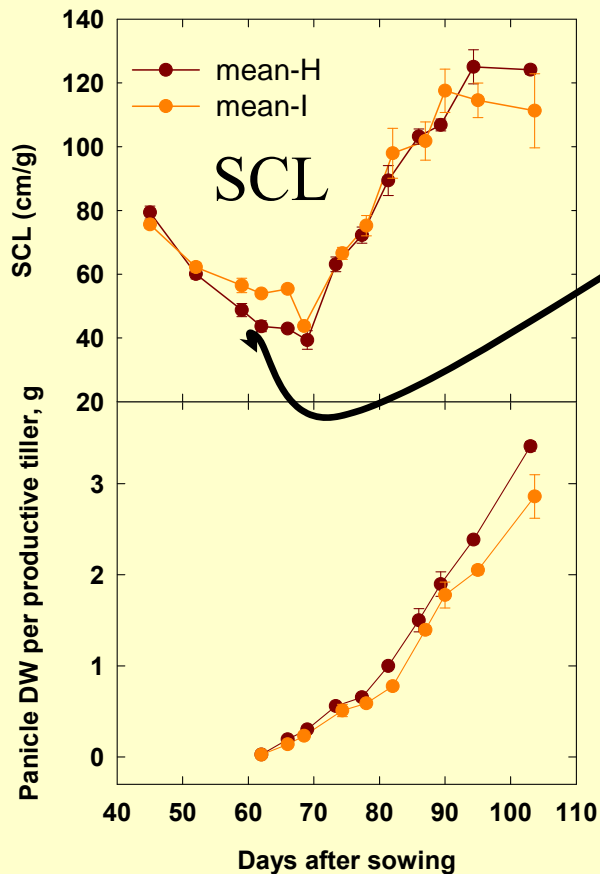
Observed variability in the dynamics of root senescence during grain filling



Delaying root senescence to improve yield potential is a trait of interest for further investigation

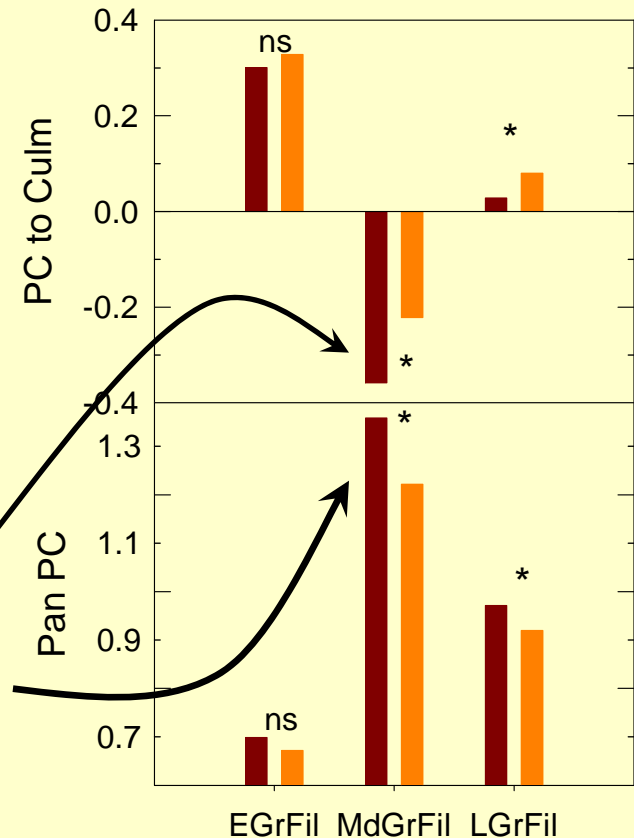
Has root senescence any impact on leaf senescence?

Early cessation of tillering, high reserve storage in the culm until flowering and high remobilization during grain filling



Hybrid: lower SCL, stronger stem and expected higher reserves storage before flowering

Hybrid: stronger remobilization from culm to panicle during grain filling



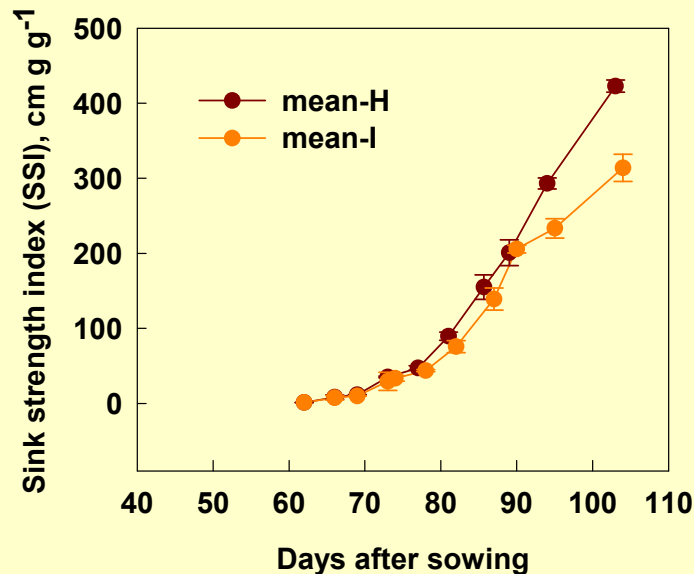
- Linking plant parameters to the dynamics of soluble sugar and starch content in various plant organs
- Identifying and calibrating some indices to account easily and simply for storage and remobilization ability?

High efficiency in partitioning during grain filling and resistance to lodging

Designing indices to account for partitioning efficiency and lodging resistance: to determine threshold values associated with risk to lodging

Designing the sink strength index as an integrated index that better represents the efficiency in partitioning than harvest index

$$\text{SSI} = \text{PaDW} \times \text{Culm length} / \text{Culm DW}$$



The weaker stem of hybrid bears a heavier panicle: lodging risk?

Designing the lodging index of the fresh culm as an integrated index that accounts for the ability of the plant to resist to lodging

Bending moment: fresh culm strength

$$\text{BM} = (\text{Cu} + \text{Pa length}) \times \text{PaFW} \times \text{CuFW}$$



Breaking resistance (BR): fresh culm

Directly tested with a prostrate tester

$$\text{Lodging index} = \text{BM} / \text{BR}$$

Increased grain filling duration to allocate more time to fill the spikelets and increase the number of filled grains

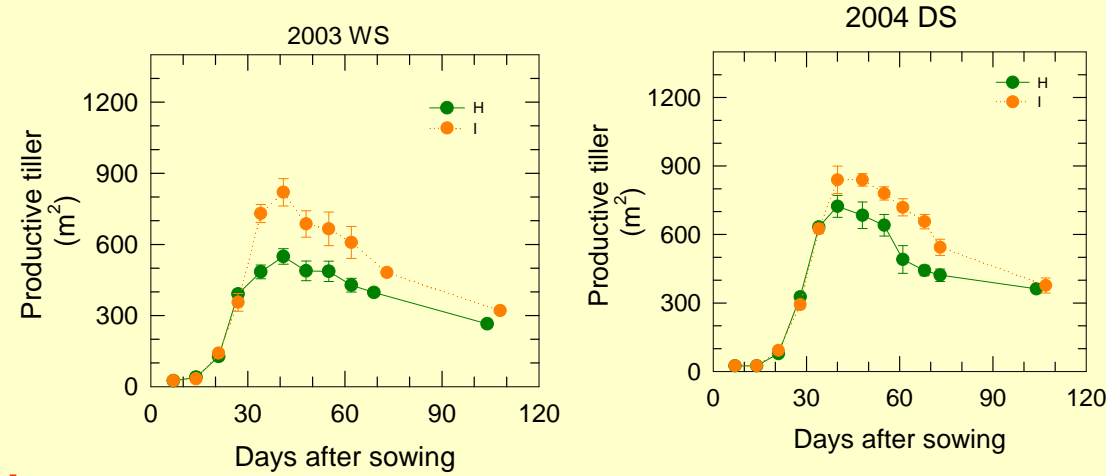
<i>wet season</i>		
Genotype	Gr Fil duration days	% of Crop dur
IR75217H	35	0.34
IR78386H	34	0.32
IR79118H	35	0.32
IR79175H	34	0.32
IR80793H	34	0.32
IR72	34	0.32
IR64	34	0.32
IR77958-7-4-3	35	0.34
IR77958-14-4-7	34	0.32
IR76999-52-1-3-2	35	0.32
IR76928-74-3-2-1	34	0.32
IR77186-122-2-2-3	34	0.31

Very few variability in grain filling duration among IRRI genotypes in breeders and physiologists' fields

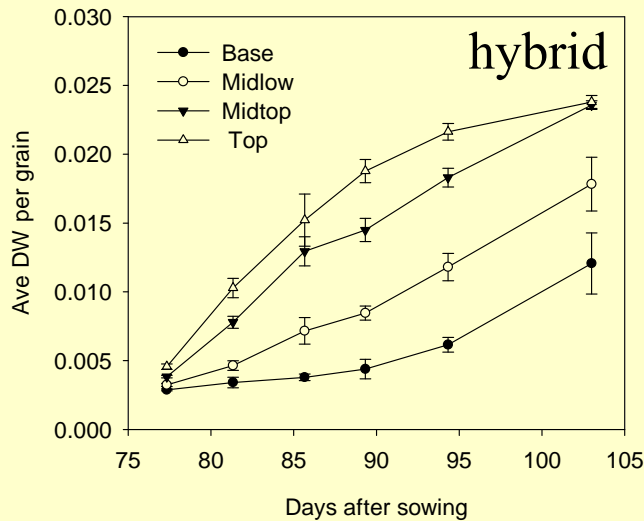
Screening for longer grain filling duration associated with delayed leaf senescence (maintaining high SPAD values during ripening)

Longer grain filling duration could be the result of:

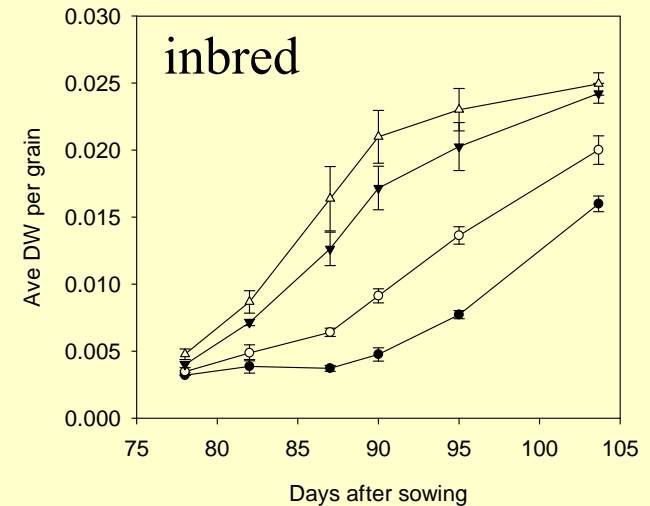
- longer overall crop duration (where only the ripening phase is extended)
- earlier start of grain filling which could be related to earlier cessation of tillering and earlier stem growth



Improved synchrony in grain filling within a panicle and within a plant to reduce shattering and increase the filled grain number

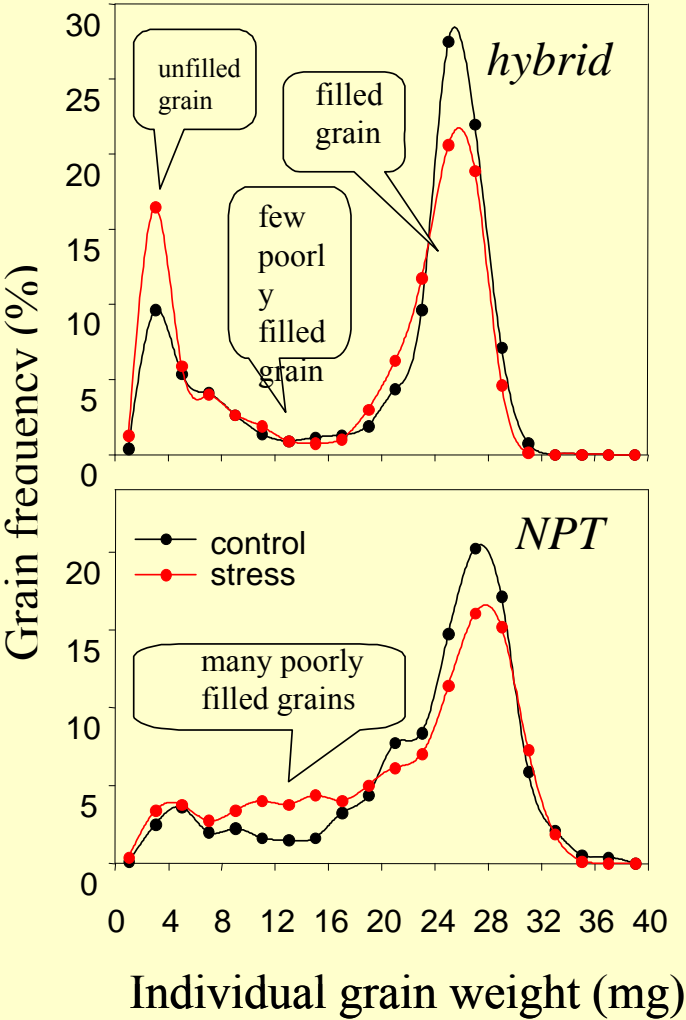


Large disynchrony in grain filling along the panicle: 15 days between the start in grain filling of top and base (only 5 days of delay in flowering between top and base)



- **A longer grain filling duration shall reduce the unfilled grain ratio at the base of the panicle, but also may reduce the viability of the filled grain at the top of the panicle if the synchrony in grain filling is not improved**
- **This may imply to breed for reduced apical dominance of grain filling: longer filling duration of a single spikelet but more grain filled at the same time**
- Shall we breed for:
 - earlier start of grain filling at the base of the panicle?
 - more filled grain at the base of the panicle?
 - more secondary spikelets along the panicle?

Reduced biomass wastage from partial internode elongation and partial grain filling of finally non-productive tillers and spikelets



Year/ Season	Genotype	1000 FiGrDw	1000 UFiGrDw
2007 DS	H(7)	24.45	4.33
	I(6)	24.40	4.55
2006 DS	H(2)	24.82	5.01
	I(3)	26.84	5.28
2005 WS	H(3)	27.37	4.26
	I(2)	27.00	4.44
2005 DS	H(2)	24.21	4.98
	I(2)	23.41	5.06
2004 WS	H(5)	24.70	4.17
	I (7)	24.70	4.77

Low unfilled spikelet dry weight as an indicator of high efficiency in partitioning

Summary of desire traits for increasing yield potential by increasing light interception and better allocating carbohydrates

1. Higher biomass accumulation (promising traits likely to increase light interception and crop photosynthesis)

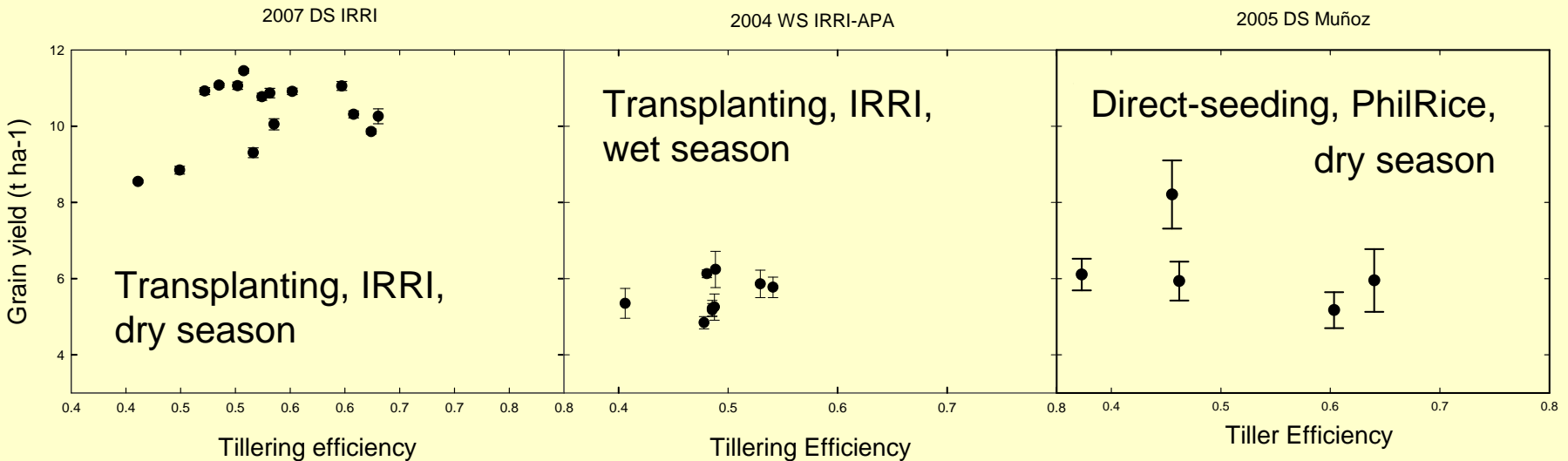
- Higher leaf area at early stage
- More efficient plant architecture (including direct-seeding)
 - prostrate leaves at early stage to capture more light and erect leaves at later stage to leave more light going through the canopy
- Leaf greenness during grain filling
 - sustain high C translocation during grain filling
- Longer grain filling duration
 - about 30 days in breeders' fields

2. More efficient sink regulation (ability of the plant to partition biomass with time as a response of the dynamics of sinks strength)

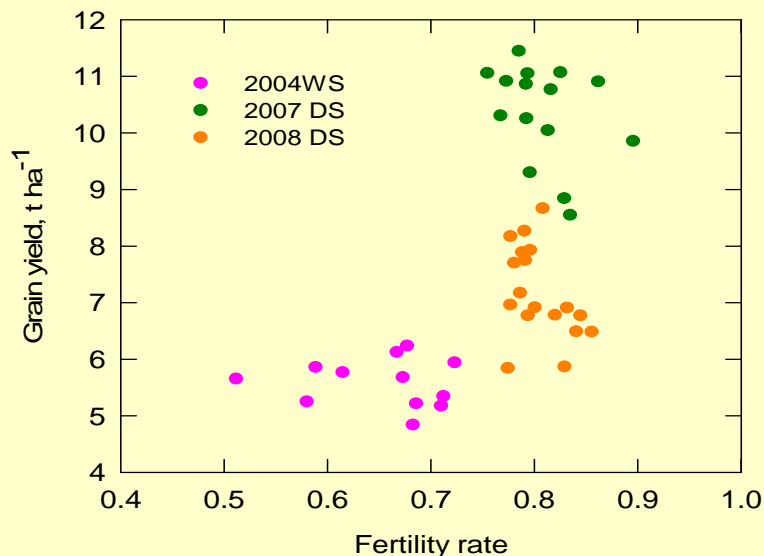
- Thin organs at vegetative
 - higher SLA (thinner leaves) at early stage: SLA of IR64 increased from 250 to 300 cm² g⁻¹ under 70% reduction in direct radiation
- Thick organs at reproductive and quicker accumulation to internodes
- Large remobilization from straw to panicle but with strong internodes at the culm base
- Early grain filling and more efficient spikelet filling to reduce weight of single unfilled spikelet

Non-promising traits for high yield potential

1. High tillering efficiency (ratio of productive above total tillers)



2. High grain filling ratio (ratio of filled above total grains)



No positive correlation is observed between:

- grain yield and tillering efficiency
- grain yield and grain filling ratio

Sink size, biomass accumulation and sink regulation

Actual sink size (number of mature spikelets) of rice crops is already high and did not appear as a limiting factor for grain yield:

- a substantial number of spikelets is unfilled (grain filling ratio around 80 %)
- the process of grain filling is reported highly active until maturity
- production of juvenile spikelets is 65% below the potential of spaced plants (Sheehy et al, 2001)
- abortion of juvenile spikelets is more than half of the total (Sheehy et al, 2001)
- husk size can be adjusted to the grain filling rate (Ishimaru, NILs for storage capacity)

It appears that the plant adapts its actual sink size to its genetic potential (biomass accumulation and sink regulation) and to its adaptation to actual weather conditions

The sink size does seem to be a driver for grain yield, but rather a consequence of the plant ability to accumulate biomass and regulate sinks

The sink size can, however, be used as a good integrated indicator for yield potential

The breeding strategies for higher yield potential should go for integrated traits like grain yield and sink size, and for traits that are directly involved in higher sink regulation and higher ability to accumulate biomass

These strategies should not focus on increasing tillering efficiency and grain filling ratio.

It seems essential to develop materials that maintain substantial amount of spare tillers and spikelets to adjust to the growing conditions and to tolerate disease and pest attacks

Difficulties to identify promising traits and plant types for selection

1. Compromising for the mutual benefit of opposite traits

- **Unproductive tillers (potential pool for reserves storage?):**
 - if increasing: higher crop light interception of short non competing tillers inside the canopy
 - if decreasing: lower waste of biomass of non-productive tillers
- **Plant height**
 - if increasing: higher light interception by increasing space between leaves
 - if decreasing: lower waste of biomass by shortening stem length
- **Remobilization**
 - if increasing: higher grain filling and filled grain number
 - if decreasing: higher susceptibility to lodging
- **Leaf senescence**
 - if increasing: higher carbohydrates remobilization to grain
 - if decreasing: lower light interception and biomass accumulation
- **Unfilled spikelets**
 - if increasing: higher sink allowance to tolerate pest attack and accomodate unexpected high carbohydrates supply
 - if decreasing: lower waste of biomass by eliminating unfilled spikelets
- **Grain filling duration**
 - if increasing: higher biomass accumulation and filled grain number
 - if decreasing: lower filled grain number through shattering of mature grains

Difficulties to identify promising traits and plant types for selection

2. Compensation mechanisms between target yield components

Examples of measured field data and possible target components:

	IR72	NPT	HYB1	HYB2	Target 1	Target 2
Grain yield, t ha⁻¹	8.5	8.2	10.1	9.7	12.0	11.9
Total panicles/m ²	400	250	450	600	350	250
Total spikelets/pan.	100	150	80	65	150	200
% filled spikelets	85	80	74	67	80	80
1000 FiGrDW, g	22	24	26	21	25	26

High compensation between yield components (panicle number, grain number per panicle, grain size) indicates that many combinations can produce the same grain yield

Fixing a quantitative target for a single yield component should not be a strategy for increasing yield potential

In the objective of designing ideotypes for yield potential, it is needed to combine integrated approaches for complex traits with single-trait approaches for well-recognized traits of interest

Actual activities for improving yield potential

1. Breeding directly for grain yield (highly integrated) and screening for panicle length and panicle fresh weight

- **Screening for grain yield in breeders' yield trials and implementing multi-locational evaluation**
 - Establishing the next generation of elite rice lines
 - Identifying lines adapted to direct-seeding
- **Measuring panicle length and panicle fresh weight from F4 nurseries (20,000 entries with 30 plants each) and F5 nurseries (10,000 entries with 30 plants each) to improve the traditional visual selection:**

This integrates compensation between grain number, grain size and grain filling rate

- Collecting the panicle length of all the panicles of one plant
- Using a portable digital balance in the field to collect panicle fresh weight of the whole plant in situ and select with quantitative criteria (with reference to a threshold value) the F4 and F5 materials to move forward

Actual activities for improving yield potential

2. Screening for well-established traits involved in biomass accumulation

- **Screening for an integrated architectural crop type during grain filling (the Chinese Super Rice model)**
 - Substantial plant height, erect leaves, 3 to 4 leaf tips above the panicle (low position of the panicle and delayed leaf senescence)
- **Screening for longer grain filling duration**
 - Duration from flowering to maturity and SPAD values during grain filling are collected on 32 promising entries selected from RYT (based on yield, dry matter production and grain fertility ratio)

Actual activities for improving yield potential

3. Calibrating key indices for high storage capacity, high remobilization and resistance to lodging (sink regulation)

- **Evaluating the variability in sink strength index and specific culm length at flowering for storage capacity**
- **Scoring lodging events in inbreds and hybrids yield trials**
- **Evaluating the variability in lodging index for lodging resistance:**
 - Culm breaking resistance (push meter), culm bending moment (integration of culm fresh weight and culm length), culm diameter (caliper) at a constant height
- **Evaluating the variability in sink strength index at maturity with respect to fresh and dry stem weight**

→ Establishing a relationship between lodging resistance and indices of culm/plant characteristics

Actual activities for improving yield potential

4. Moving towards gene discovery of promising traits through the establishment and analysis of NILs

- **Control in tiller production: discovering genes involved in lower tiller emergence rate (IR64 NILs)**
 - Could this be extended to the discovery of genes involved in earlier cessation in tiller emergence? This may be related to the sensitivity to the red/far-red light ratio of the plant
- **Control in leaf senescence: discovering genes involved in delayed leaf senescence (Milyang23 NILs, O.glaberrima as the other parent)**
 - Introducing delayed leaf senescence characteristics in Milyang23 which is a fast leaf senescence variety: promising comparative performance of the NILs
 - Developing DNA markers in a F2 population of NIL x Azucena (fast leaf senescence)
 - Increasing grain filling duration indirectly through the increase in leaf longevity
- **Control in stem elongation rate: discovering genes involved in higher stem elongation rate and in earlier stem elongation (Milyang23 NILs)**
 - Could this be related to the control in earlier cessation in tiller emergence?

Actual activities for improving yield potential

5. Identifying new traits and new concepts of ideotypes with an intensified comparison of elite hybrids and elite lines

- **Enlarging the range of high-yielding germplasm under study**
- **Implementing the evaluation of germplasm in multi-locational sites**
- **Focusing on processes involved in biomass accumulation and sink regulation**
- **Connecting these processes to yield components characteristics**
- **Associating these processes to easily quantifiable traits for screening purposes**

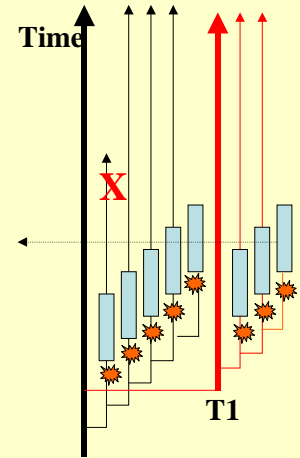
Actual activities for improving yield potential

6. Identifying new traits and new concepts of ideotypes by exploring multi-trait combinations in mechanical modeling

- **Considering modeling for evaluating the impact of elementary traits in a complex system**
- **Developing a model enabling to account for**
 - **carbohydrates source-sink relationships and plant morphogenesis,**
 - **regulation by genotypic and environmental determinisms**
 - **feedbacks on crop architecture**
- **Linking plant topology with plant architecture by combining architectural and functional models**

EcoMeristem (Cirad):

driving carbon partitioning and plant morphogenesis through confrontation of supply and demand to organ initiation and dimensioning



GECROS (Wageningen University):

computing for energy balance and carbon-nitrogen interaction at leaf level to determine local sink demand in function of local environment

AMAP (Cirad): generating 3D representation Of plants for computing radiation transfer and energy balance at organ level and then local resources acquisition

7. Exploring potential new traits of interest and evaluating genetic variability

- Higher SLA at early stage to improve tillering capability and weed competitiveness
- Clump plasticity towards open clump and prostrate leaves at early stage and erect clump and leaves during grain filling
- Earlier cessation of tillering
- Respiration
- Carbohydrate remobilization from non-productive to productive tillers
- Delayed root senescence and root to shoot remobilization
- Synchrony of spikelet filling between the top and bottom of the panicle
- Individual filled and unfilled grain size
- Increased leaf photosynthesis: C4 rice

Summary of current activities for improving yield potential

1. Breeding directly for grain yield	P Virk, D Brar, S Peng	Core, CSISA, GSR, HRDC
2. Screening for traits for biomass accumulation	S Peng, T Lafarge, P Virk	Core, Cirad
3. Calibrating key indices (remobilization, lodging)	S Peng, T Lafarge	Core, Cirad, HRDC
4. Gene discovery	KH Kang, N Kobayashi	RDA (Korea), GUVa, IRRI-Japan project
5. Comparison of hybrids and inbreds	S Peng, T Lafarge	Core, Cirad, HRDC
6. Mechanical modeling	T Lafarge	Core, Cirad
7. Exploring new traits	S Peng, J Sheehy, T Lafarge	Core, Cirad, C4 rice

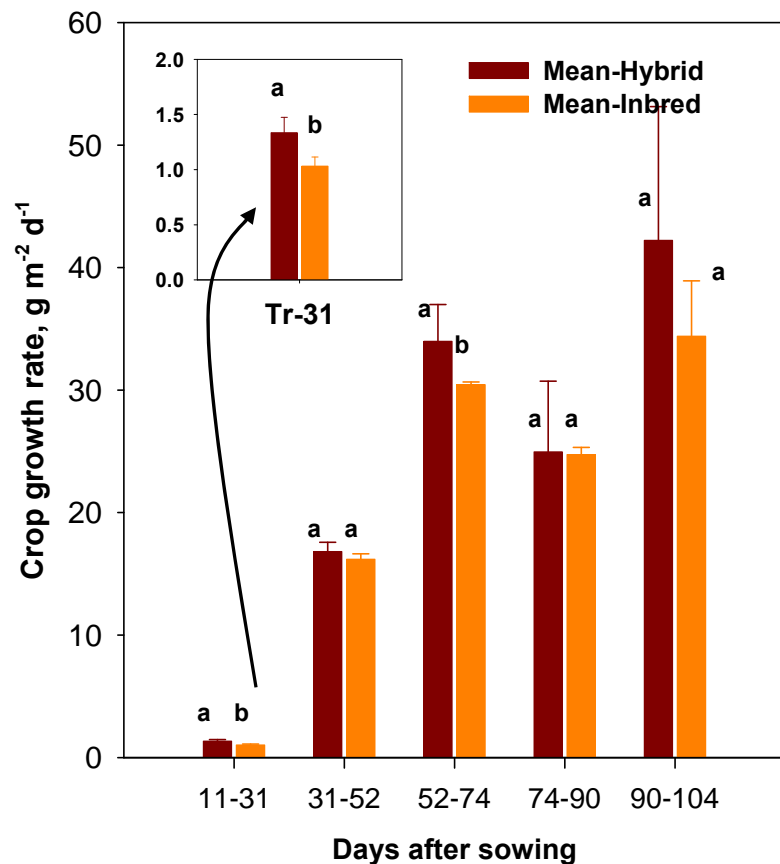
Background on strategies for high yield potential:

2. Hybrid morphology and behavior as the reference for high yield

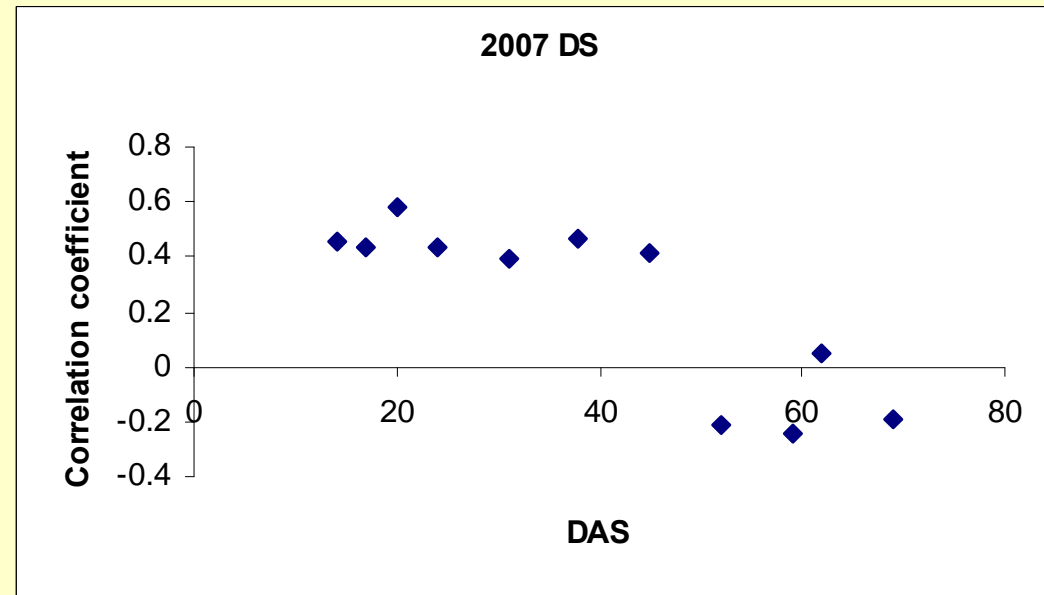
- IRRI hybrid rice: higher biomass accumulation during the 3 growth phases**

Comparing 4 hybrids and 4 inbreds:

$$\text{CGR} = \frac{\Delta dw_{\text{shoot } 2 \rightarrow 1}}{\Delta \text{time}_{2 \rightarrow 1}}$$



Correlation of grain yield with leaf area index during the whole vegetative phase when comparing a range of hybrids and inbreds



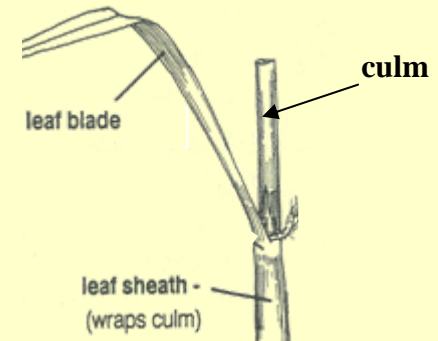
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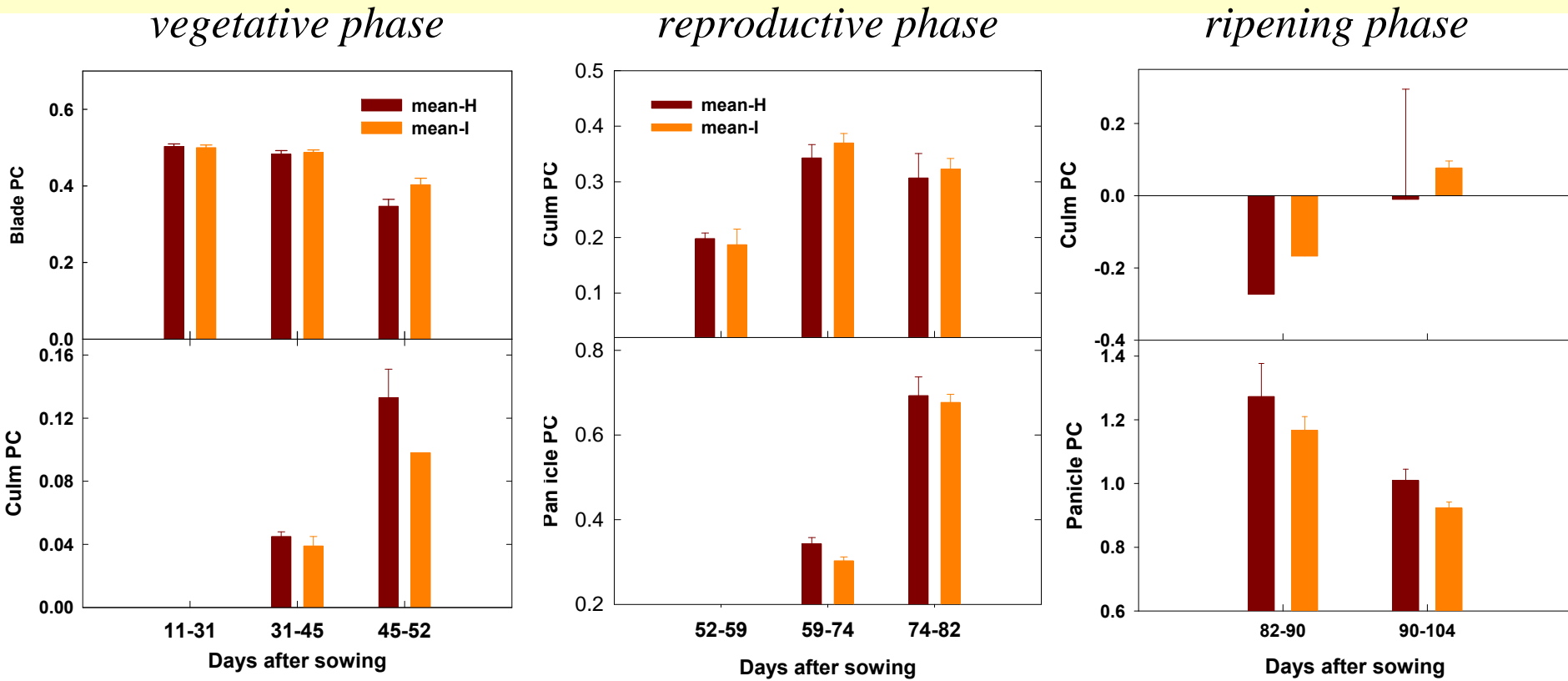
- IRRI hybrid rice: higher sink regulation during the 3 phases of development**

Calculation of blade partitioning coefficient:

$$\text{Blade PC} = \frac{\Delta dw_{\text{blade } 2 \rightarrow 1} / \Delta \text{time}_{2 \rightarrow 1}}{\Delta dw_{\text{shoot } 2 \rightarrow 1} / \Delta \text{time}_{2 \rightarrow 1}}$$



Comparing 4 hybrids and 4 inbreds:



General conclusion

- No detrimental effect of the number of non-productive tillers on grain yield and harvest index as long as high-yielding genotypes are concerned
- Higher biomass accumulation in hybrid rice:
 - does leaf angle play a role and during the whole crop cycle?
 - do leaf senescence and remobilization from leaf play a role during grain filling?
- **More efficient sink regulation (to be associated to sugar metabolism, data to come soon) is essential to increase high yield potential:**
 - Early and quick tiller emergence, already with most high-yielding inbreds and hybrids
 - quicker increase in allocation to the culm before PI
 - quicker increase in allocation to the panicle during culm growth
 - more biomass remobilized from the culm
 - more spikelets filled at a time during the whole filling period
 - lighter unfilled grains

} more efficient in hybrid rice
- Higher early hybrid vigor:
 - the individual seed size and SLA do not play a role
 - Is it due to more efficient sink regulation?
- High susceptibility to lodging in high-yielding hybrid rice:
 - some hybrids show some resistance (Islam et al 2007): lower SCL of lower internodes.
What about their sink regulation and yield potential? Considering environmental risk for lodging?
- Crop management:
 - hybrids and inbreds respond similarly to seedling age at transplanting and to direct-seeding
 - nitrogen management has been identified as a practice to adapt to plant type (Peng et al) with spikelet number increasing linearly with increase in N concentration (Horie et al 2003)